hep-ph/9412234
LA-UR-94-3953; LAEFF-94/14

THEORETICAL MOTIVATION FOR GRAVITATION EXPERIMENTS ON ULTRA-LOW ENERGY ANTIPROTONS AND ANTIHYDROGEN

MICHAEL MARTIN NIETO and T. GOLDMAN*
Theoretical Division
Los Alamos National Laboratory
University of California
Los Alamos, New Mexico 87545 USA

JOHN D. ANDERSON and EUNICE L. LAU†
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109 USA

J. PÉREZ-MERCADER‡
Laboratorio de Astrofísica Espacial y Física Fundamental
Aptdo. 50727
28080 Madrid, Spain

ABSTRACT

We know that the generally accepted theories of gravity and quantum mechanics are fundamentally incompatible. Thus, when we try to combine these theories, we must beware of physical pitfalls. Modern theories of quantum gravity are trying to overcome these problems. Any ideas must confront the present agreement with general relativity, but yet be free to wonder about not understood phenomena, such as the dark matter problem and the anomalous spacecraft data which we announce here. This all has led some "intrepid" theorists to consider a new gravitational regime, that of antimatter. Even more "daring" experimentalists are attempting, or considering attempting, the measurement of the gravitational force on antimatter, including low-energy antiprotons and, perhaps most enticing, antihydrogen.

1. Introduction

Classical, worldline, general relativity, and many-path quantum mechanics, are, by the descriptive words, worldline vs. many-path, fundamentally in conflict with

*Email: mmn@pion.lanl.gov; goldman@hotelcal.lanl.gov
†Email: JDA@grouch.jpl.nasa.gov; eunice@helen.jpl.nasa.gov
‡Email: mercader@estrella.laeff.esa.es

each other. It makes no difference if this distinction would manifest itself only at the Planck scale. It is still there.

Indeed, much of the effort of modern theoretical physics is devoted to overcoming this conflict, at least in principle. On the one hand, theories of quantum gravity try to incorporate a gravitational interaction, albeit in some higher symmetry or space-time, and then have general relativity fall out as a classical approximation. On the other hand, cosmologists of the "wave function of the universe" school, are trying to modify quantum mechanics to allow a unified picture of physics.

Independent of whether either of these schools is on the right track, it is logically clear that either 1) general relativity, or 2) quantum mechanics, or 3) both theories have to be modified to obtain a better theory of physics. Ironically, our guide may be in looking at the great body of experimental data which defines the successes of these theories: from the successes of QED [1] to the successes of general relativity.[2,3]

It is as a devil's advocate that I (MMN) discuss the situation for this present collaboration. I will argue that in many regimes we know much less than we generally assume we know. This opens up the possibility that there may be something totally unexpected waiting for us when we ultimately reach the essential confrontation of these two fields, in the gravity of antimatter.[4]

2. What Do We Not Know?

Given the many successes of general relativity, then, why would one even question that gravity on antimatter might be different than gravity on matter? To begin, one can give a two-fold rationale. The first is exemplified in Aspect's experimental test[5] of Bell's inequalities.[6] The result (that quantum mechanics is correct) was "known" before the experiment. But yet, it was important to do the experiment. Secondly, even in areas where one already has an answer to a known accuracy, it is important to significantly improve the experimental agreement. That was emphasized by Dicke,[7] who argued, "It is clear ... that if one believes that general relativity is established beyond question by its elegance, beauty, and the three famous experimental checks, then the Eötvös experiment has no point! ... However, if gravitational theory is to be based on experiment, ... " And so, Dicke did his experiment.

2.1. Gravity and CPT

Furthermore, and as indicated in the introduction, modern attempts to unify gravity with the other forces lead to the generic conclusion that $g(p) \neq g(\bar{p})$, at *some* level. Now this statement does not contradict CPT, even though one might have thought so.

CPT tells us that an antiapple falls to an antiEarth in the same way that an apple falls to the Earth. It says nothing about how an antiapple falls to the Earth.

But I already have cheated on you. No general CPT Theorem has been proven for curved space-time general relativity. In fact, in some string theories, CPT is known

to be violated. It is OK to use CPT for intuitive arguments, but not for precise, general arguments. That is to say, one can expect that the statements about apples and antiapples given above are approximately correct, but one has to be careful if statements are given about orbiting black holes vs orbiting antiblack holes.

What else do we really not understand?

2.2. CP violation

We really don't understand CP violation as manifested in the $K_0 - \bar{K}_0$ system. Remember, a parametrization, the CKM-matrix, is *not* an explanation. Furthermore, upon the existence of CP violation depends our supposed understanding of the dominance of matter over antimatter in the universe.

Recall that, since the early days, some have suggested that there is a connection between the neutral-K system and gravity.[8,9]. More recently some string theories have found CPT and CP violation,[10,11] although, from experiment, the amount allowed by the first of these theories[10] has been shown to be small.[12]

Even more interesting is the unusual suggestion of Chardin,[13] that CP violation is a reflection of a microscopic violation of the arrow of time, that is, antigravity. What is lost is the permanence of matter. There is a Hawking-like radiation with a connection to entropy.

What else don't we understand about gravity?

3. Actually, We Don't Understand Gravity and Matter (let alone antimatter) for Almost All of the Universe!!

This is the dark matter[§] problem, the presentation and possible resolutions of which can be traced to the beginnings of the last century. What does one think if one observes an object that is behaving "incorrectly" from a gravitational point of view? Either 1) there is unseen matter causing the odd motion, or 2) there is a breakdown in Newton's Law. When the orbit of Uranus was found to be behaving strangely 150 years ago, both John Couch Adams and Urbain Jean Joseph Leverrier decided that there had to be a new, unseen planet causing the perturbations . . . and indeed there was, Neptune.[14] But just ten years later, a new planet, "Vulcan," was not the cause of the anomalous advance of Mercury's perihelion. It took another 50 years for this explanation to come, the breakdown of Newton's Law in general relativity.

3.1. Dark matter and large-distance scales

Such is the problem today, on the grandest scales of the universe. One can observe beautiful gravitational lensing of distant galaxies by foreground clusters of galaxies.[15] But the visible matter in the clusters is only a small fraction of what would be needed to have lensed the distant galaxy. Either there is dark matter in the clusters or else the

[§]More generally one might use the term "dark mass" or the "mass-energy" of Wheeler.

interaction causing the lensing (it does not have to be general relativity) is stronger than believed.¶No one knows. A lot of people think, but no one knows.

On smaller, but still long-distance scales, there are the puzzling rotation curves of galaxies. By Doppler measurements one can find the velocity of stars in spiral galaxies as a function of their distance from the galactic centers. Over a large variation of distance, this velocity is often approximately constant. But when one tries to account for such a velocity distribution from the visible matter in these galaxies, there is not enough visible matter to account for the motions. Therefore, one normally presumes that there is dark matter in the galaxies.

However, it has been observed by a number of people that certain non-Newtonian potentials could account for the motions using the visible matter alone.[16,17,18] These calculations are not precise, since visible mass determination is also not precise. but the results are intriguing. I will go over one of them, the Modified Newtonian Dynamics (MOND) of Milgrom and Bekenstein.[18] This model is controversial, but it serves as a good reference point for what comes later.

Basically, this dynamics comes from a model equation of the form

$$\mu(g/a_0)\mathbf{g} = \mathbf{g_N} \ , \tag{1}$$

where g_N is the Newtonian acceleration, g is the true acceleration, μ is a monotonic function that satisfies

$$\mu(x) \rightarrow \begin{cases} x \ , & x \rightarrow 0 \\ \\ 1 \ , & x \rightarrow \infty \end{cases} \ . \tag{2}$$

a_0 is a new, critical acceleration constant, that I will return to quickly. The idea is that you have a Newtonian force for large accelerations and a $1/r$ force for small accelerations. Specifically, one has

$$g = \begin{cases} GM/r^2 \ , & g \gg a_0 \\ \\ \left[GMa_0\right]^{1/2}/r \ , & g \ll a_0 \end{cases} \ . \tag{3}$$

a_0 is proportional to the Hubble-Constant-squared. But for this constant equal to 100 (in the usual units), the value of a_0 is

$$a_0 = (2-8)\times 10^{-10} \ (m/sec^2) \ . \tag{4}$$

This new force allows many galactic-rotation curves to be explained.[19]

3.2. Astronomical-Unit scales

The distance scale at which the Sun's Newtonian force would equal its $1/r$ MOND force is a few thousand Astronomical Units. One might hope to find corrections at

¶This leaves aside interesting and complicating issues such as the controversial, new values given for the Hubble Constant.

smaller distances than this. This fact suggests one look for such deviations from Newton's Law at the many AU scale, no matter what the origin might be. Indeed, in so doing we are simply following the suggestion of Poincaré:[20] "…the true aim of celestial mechanics is not to calculate the ephemerides, because for this purpose we could be satisfied with a short-term forecast, but to ascertain whether Newton's law is sufficient to explain all the phenomena." (Note that this is in a different regime than the much shorter laboratory and geophysical scales which have recently been the object of much study.[21,22])

The first place might be double stars. These objects have been know for about 200 years. The problem is to track their orbits. "Long-period binaries" are not even known for certain to be bound. That they travel together is what we know about them. Even the orbits of shorter-period binaries have not been studied extensively enough to look for deviations from Newtonian dynamics. This may be a problem for further investigation. (Note, also, that this is a different regime than the well-studied binary pulsars or even close, relativistic binaries [23]. The present study deals with weak-field systems.)

When it comes to comets, the longest-period repeating comet is the comet discovered by Caroline Herschell in 1788 and rediscovered by Rigollet in 1939.[24] It goes out to a distance of 57 AU from the Sun. However, because of perturbations from the major planets and loss of mass in its orbit, all this comet can tell us is that Newton's Law is approximately correct, say to a few percent, out to such distances. (For example, its calculated orbital period is 155 years vs. the observed 151.)

4. Spacecraft Tests of Gravity

Better limits on Newtonian gravity on these scales can be obtained with the data from deep space probes.

4.1. Astronomical-Unit scales

For example, Pioneers 10 and 11 were launched in 1972, and were the first close encounters with the major planets, most specifically Jupiter. After Pioneer 10's encounter with Jupiter, and Pioneer 11's encounter with Saturn, they eventually went into orbits in opposite directions from each other, near the ecliptic.[‖] They are in a gyro mode (rotating every 13 seconds), so their motions are not disturbed by attitude-control thrusters, as in the case of the Voyager 1 and 2 spacecraft. The Pioneers' velocities have been monitored by the NASA/JPL Deep Space Network (DSN) using transponded coherent radio Doppler data (13 cm wavelength) referenced to hydrogen-maser clocks at stations in California, Australia, and Spain. These data exist out to 30 AU for Pioneer 11 and have been analyzed out to 57 AU for Pioneer 10. The latter spacecraft is still returning high-quality coherent Doppler data at 61

[‖]After Saturn flyby, Pioneer 11 was inclined to the ecliptic and, at the end of Doppler tracking in August, 1990, was at ecliptic latitude 16 arcdegrees.

AU distance, and additional data analysis is underway.

Preliminary analysis by the JPL team indicates a systematic deviation from Newtonian dynamics. In order to fit the Doppler data from both Pioneer spacecraft, they require an excess acceleration of 8×10^{-10} m s^{-2} directed toward the Sun.[**] Although some of this excess could be explained by nonisotropic thermal emission, it is very difficult to account for all of it that way.

A similar (but possibly smaller) constant acceleration has been observed on the Galileo spacecraft during its cruise trajectory between Earth and Jupiter. However, the Galileo excess acceleration could be caused by a nonisotropic thermal component of about 200 W. Knowing that about 500 W is being delivered to the spacecraft bus by Radioactive Thermoelectric Generators (RTG), the JPL team would find this to be a remarkably large nonisotropic component, but still plausible.

Further, the JPL people are currently analyzing data from the Ulysses spacecraft during its out-of-ecliptic journey from 5.3 AU, near Jupiter's orbital radius, to its perihelion distance at 1.3 AU. So far it seems that a constant acceleration, similar to that acting on Pioneer and Galileo, is also acting on Ulysses. But they need more data analysis to be sure.

Let me emphasize again that all these results and conclusions are preliminary. When all their analysis is complete, the JPL team will publish the details and their final conclusions. Quite properly, the JPL scientists are devoting much effort into searching for a nongravitational origin of their systematics.

Also, another problem they are considering is how planetary orbits would be affected by a constant radial acceleration of the magnitude indicated by the spacecraft. A preliminary analysis indicates that systematic error in the orbits of the outer three major planets could easily mask the constant acceleration. Only Jupiter, with its eleven year sidereal period and with spacecraft fixes on its orbital motion, might reveal a constant acceleration of this magnitude or, on the other hand, rule it out at a 5.2 AU distance. Radio ranging data generated with the Martian Viking Landers probably rule out a constant acceleration from the Sun on the planets at Earth distance (1.0 AU) and Mars distance (1.52 AU).

Weak limits on Newtonian gravity have previously been set on the outer planets by means of searches for dark matter [25,26] and a discussion of possible modifications of Newtonian gravity.[27] But even if more detailed data analysis confirms that planetary orbits are incompatible with the accelerations acting on spacecraft, one might still conclude that spacecraft and planets react differently to some previously unknown component of the gravitational interaction. With this possibility in mind, more work is being planned on both the theoretical and observational questions.

4.2. Planetary scales

Anomalies also exist in the Galileo trajectory during the two close flybys of Earth in December 1990 and December 1992. The necessity of increasing total orbital energy

[**] The similarity of this number to the MOND critical acceleration is amusing, if not intriguing.

at the first flyby in order to fit the radio data, by an equivalent velocity increase of 4 mm/s, led JPL to schedule tracking of the second flyby with the Tracking and Data Relay Satellite System (TDRSS) from earth orbit.[28] After analyzing the TDRSS data, they were left with systematic effects not removable by the standard Earth gravity model determined from Earth satellites (Goddard JGM-2 70X70 gravity field truncated to a 40X40 field).

Having ruled out the usual nongravitational forces acting on spacecraft, they currently have no physical explanation for either anomalous Earth flyby. Also, they have tested against software bugs by successfully comparing results from JPL's Orbit Determination Program (ODP) with results from Goddard's GEODYNE software.

Similar data anomalies during flybys of other planets are not detectable because of uncertainties in their gravity fields, with the possible exception of the Mariner 10 Mercury flyby in March 1975. There they removed Doppler systematics with an unexpectedly large gravity anomaly, about one-tenth the largest Earth anomaly (the antarctic low). This is large for Mercury but not way outside the bounds of plausibility.[29] Future Mercury orbiters should tell us whether or not such a large gravity anomaly is real.

5. Gravity and Antimatter

To place the last two sections in perspective, whatever is going on here the whole discussion should make it clear to you that our understanding of gravity within the universe is incomplete.

This brings us full circle. Given that our theoretical and experimental knowledge of the physics of gravity and antimatter are woefully inadequate, to perform an experiment on the gravity of antimatter would be a monumental milestone in our understanding of physics. This would be true even if we found exactly what we expect, that gravity on antimatter is the same as that on matter. Until we actually do such an experiment, we do not know the answer, we only believe we do.

The proposal to measure the gravitational acceleration of the antiproton[30] has progressed to the PS200 experiment.[31] The first part of this experiment is already on the floor at LEAR, the "catching trap."[32]

There are also two main ideas on how to form antihydrogen: via positronium-antiproton[33] collisions or directly from positron-antiproton collisions.[34] Then it might be possible to control this antihydrogen by laser cooling, magnetic traps, or "fountains." If so, a long-term goal would be to measure gravity on antihydrogen. (See the discussion in Refs. [32,35] for a comparison of these ideas.)

But in any event, it is in the hands of our generation to perform an experiment to measure the gravitational acceleration of antimatter. Some day it will be done, whether we do it or not. *It will be done.* If we do not do it, and the answer eventually turns out to be what we expect, then future generations will look back upon us a say it was a shame. But if the answer turns out to be a surprise, then, if we do not do it, future generations will look back upon us and say we were fools.

Acknowledgements

There are many individuals who deserve thanks for their help on this project. With apologies to those whom I leave out, let me mention Jack Hills, Gabe Luther, and Raymond Laflamme. JDA and ELL benefitted from many theoretical discussions with Timothy P. Krisher. Their research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Pioneer Project Office, NASA/Ames Research Center, LOA PPO-17, through an agreement with the National Aeronautics and Space Administration.

[1] T. Kinoshita, *Phys.Rev.D* **47** (1993) 5013.
[2] C. M. Will, *Int. J. Mod. Phys. D* **1** (1992) 13.
[3] J. D. Anderson, J. K. Campbell, R. F. Jurgens, E. L. Lau, X X Newhall, M. A. Slade III, and E. M. Standish Jr., in: *Proceedings of the Sixth Marcel Grossmann Meeting on General Relativity, Part A*, eds. H. Sato and T. Nakamura (World Scientific, Singapore, 1992), p. 353.
[4] M. M. Nieto and T. Goldman, *Phys. Rep.* **205** (1991) 221; *ibid.* **216** (1992) 343.
[5] A. Aspect, P. Grangier, and G. Roger, *Phys. Rev. Lett.* **47** (1981) 460; A. Aspect, J. Dalibard, and G. Roger, *Phys. Rev. Lett.* **49** (1982) 1804.
[6] J. S. Bell, *Physics* **1** (1965) 195.
[7] P. G. Roll, R. Krotkov, and R. H. Dicke, *Ann. Phys. (N.Y.)* **26** (1964) 442.
[8] M. L. Good, *Phys. Rev.* **121** (1961) 311.
[9] J. S. Bell and J. K. Perring, *Phys. Rev. Lett.* **13** (1964) 348.
[10] J. Ellis, N. E. Mayromatos, and D. V. Nanopoulos, *Phys. Lett. B* **293** (1992) 142.
[11] V. A. Kostelecký and R. Potting, *Nucl. Phys. B* **359** (1991) 545.
[12] P. Huet and M. E. Peskin, *Nucl. Phys. B* (to be published).
[13] G. Chardin, *Nucl. Phys. A* **558** (1993) 477c.
[14] M. Grosser, *The Discovery of Neptune* (Harvard Univ. Press, Cambridge, Mass., 1962).
[15] A. Tyson, *Physics Today* **45** (1992) No 6, 24.
[16] S. Tremaine, *Physics Today* **45** (1992) No. 2, 29.
[17] P. D. Mannheim, *Astrophys. J.* **419** (1993) 150. However, also see K. S. Wood and R. J. Nemiroff, *Astrophs. J.* **369** (1991) 54
[18] J. Bekenstein and M. Milgrom, *Astrophys. J.* **286** (1984) 7; M. Milgrom and J. Bekenstein, in: *Dark Matter in the Universe*, eds. J. Kormendy and G. R. Knapp (IAU, 1987), p. 319.
[19] M. Milgrom, *La Recherche* **19** (1988) 182.
[20] H. Poincaré, *New Methods of Celestial Mechanics, Vol. 1*, translated from the original French edition of 1892 and edited by D. L. Goroff (American Institute of Physics, New York, 1993), p. xxiv in the introduction to the French edition.
[21] C. M. Will, *Sky and Telescope* **80** (1990) 472.

[22] E. Fischbach and C. Talmadge, *Nature* **356** (1992) 207.
[23] F. P. Maloney, E. F. Guinan, and J. Mukherjee, *Astron. J.* **102** (1091) 256.
[24] H. M. Jeffers, *Publ. Astron. Soc. Pacific* **51** (1939) 293; K. P. Kaster and T. J. Bartlett, *ibid.* 295; K. P. Kaster, *ibid.* 296.
[25] J. D. Anderson, E. L. Lau, A. H. Taylor, D. A. Dicus, D. C. Teplitz, and V. L. Teplitz, *Astrophys. J.* **342** (1989) 539.
[26] J. D. Anderson, E. L. Lau, T. P. Krisher, D. A. Dicus, D. C. Rosenbaum, and V. L. Teplitz, *Astrophys. J.* (to be published).
[27] C. Talmadge, J.-P. Berthias, R. W. Hellings, and E. M. Standish, *Phys. Rev. Lett.* **61** (1988) 1159.
[28] C. Edwards, J. Anderson, P. Beyer, S. Bhaskaran, J. Border, S. DiNardo, W. Folkner, R. Haw, S. Nandi, F. Nicholson, C. Ottenhoff, and S. Stephens, in: *Advances in the Astronautical Sciences*, eds. A. K. Misra, V. J. Modi, R. Holdaway, and P. M. Bainum (San Diego, Univelt, 1993), p. 85.
[29] J. D. Anderson, G. Colombo, P. B. Esposito, E. L. Lau, and G. B. Trager, *Icarus* **71** (1987) 337.
[30] T. Goldman and M. M. Nieto, *Phys. Lett. B* **112** (1982) 437.
[31] M. H. Holzscheiter, R. E. Brown, J. B. Camp, S. Cornford, T. Darling, P. Dyer, T. Goldman, S. Høbråten, K. Hosea, R. J. Hughes, N. Jarmie, R. A. Kenefick, N. S. P. King, D. C. Lizon, M. M. Nieto, M. M. Midzor, S. P. Parry, J. Rochet, R. A. Ristinen, M. M. Schauer, J. A. Schecker, and F. S. Witteborn, *Nucl. Phys. A* **558** (1993) 709c.
[32] M. M. Nieto and M. H. Holzscheiter, *Appl. Phys. B* (to be published).
[33] B. I. Deutch, L. H. Anderson, P. Hvelplund, F. M. Jacobsen, H. Knudsen, M. H. Holzscheiter, M. Charton, and G. Laricchia, *Hyperfine Int.* **44** (1988) 271.
[34] G. Gabrielse, S. L. Rolston, L. Haarsma, and W. Kells, *Phys. Lett A* **129** (1988) 38.
[35] M. H. Holzscheiter, *Hyperfine Int.* **81** (1993) 71.